REMARKS

In view of the above amendments and following remarks, Applicant respectfully requests reconsideration and allowance of the above-identified application.

Claims 1, 2, 4, 5, 9 and 12-22 are now pending in this application, with Claims 1, 2, 4, 5, 9, 12 and 20-22 being independent. By this Amendment, Applicant has canceled Claim 11 and amended Claim 13.

The Office Action indicates that should Claim 1 be found allowable, Claim 11 would be objected to under 37 C.F.R. § 1.75 as being a substantial duplicate thereof. Applicant submits this matter is now moot in view of the cancellation of Claim 11.

Claims 1, 11, 12, 13-17 and 20-22 stand rejected under 35 U.S.C. § 103 as being unpatentable over U.S. Patent No. 6,157,488 (Ishii) in view of U.S. Patent No. 5,048,925 (Gerritsen, et al.). Claims 2, 4, 5, 9 and 13-19 stand rejected under 35 U.S.C. § 103 as being unpatentable over Ishii and Gerritsen, et al. in view of U.S. Patent No. 5,279,924 (Sakai, et al.). Applicant traverses these rejections.

As generally recited in each of the independent claims, Applicant's invention is directed to a diffractive optical element having a diffractive grating portion. The diffractive grating portion includes a pair of diffractive gratings differing in dispersion from each other and confronting each other through a space having a refractive index of 1. In addition, with respect to independent Claims 1, 2, 4, 5, 9, 11, 12, 20 and 22, a maximum optical path length difference occurring in the diffractive grating portion with respect to at least two wavelengths is m (integer) times the wavelength, and the values of m in the two wavelengths are the same.

The § 103 rejections are based generally on the Examiner's position that the second optical region described in the Ishii patent (i.e., portion 12 shown in Figure 6) could be modified to have a refractive index of 1. Applicant disagrees with this assertion.

The Ishii patent describes that, in order to reduce wavelength dependency of diffraction efficiency, $\Delta N(\lambda)$ is increased with the increase of the wavelength, as shown in equation 15 of that patent. To achieve this result, the patent states that a combination of a polycarbonate and a material of a low refractive index and low dispersion (such as an acrylic resin or UV-curable resin) is used. Specifically, with respect to Figure 6, layer 12 is a UV-curable resin, not a layer with a refractive index of 1. (At column 15, lines 17-21, the Ishii patent also states that, while a UV-curable resin is most preferred, plastic materials may also be used.) The refractive index difference of diffractive grating composed of polycarbonate and the material of low refractive index and dispersion is in a state of upward sloping in which the refractive index difference increases with the increase in the wavelength. The Ishii patent states that the combination of the polycarbonate and a material of low refractive index and low dispersion (e.g., a UV-curable resin) achieves this result. If layer 12 were made to be an air gap with a refractive index of 1, this basic tenant of the Ishii patent would be ignored. Applicant notes that, for a proper obviousness-type rejection, the proposed modification of the prior art cannot render the device unsatisfactory, which Applicant submits the proposed modification in the present Office Action would do. *See In re Gordon,* 733 F.2d 900, 221, USPQ 1125 (Fed. Cir. 1984); *see also* MPEP 2143.01.

In the present invention, $\Delta N(\lambda)$ is increased with the increase in the wavelength, even if the space between the diffractive grating has a refractive index of 1.

With the presupposition of the Ishii patent, that a combination of a polycarbonate and a UV-curable resin be used, having a refractive index of 1 between the diffractive gratings is not possible.

Also, by providing a refractive index of 1 between the diffractive gratings, advantages not found in the system described in the Ishii patent are possible. For instance, since the heights of pairs of grating spacing the space having the refractive index of 1 can be lowered, the ratio of light blocked by the side edges of diffractive gratings can be lowered. This increases efficiency and diminishes color flare. Other benefits of the present invention are discussed on the attached promotional materials from the Assignee's web site (labeled Exhibit A). The promotional materials describe lens systems embodying the present invention.

The Gerritsen, et al. patent is cited as describing a diffractive optical system in which diffraction gratings are spaced apart from each other by an air gap 64, shown in Figure 6. That patent, however, does not describe a diffractive grating system of the present invention, inasmuch as the maximum optical path length difference occurring in the diffractive grating portion with respect to each of at least two wavelengths is *not* m (integer) times the wavelength, with the values of m in the two wavelengths being the same. Furthermore, air gap 64 described in that patent is used for a purpose unrelated to that of the present invention. Accordingly, Applicant submits that one of ordinary skill in the art would not be motivated to combine the teachings of the Gerritsen, et al. and Ishii patents. Further, as discussed above, providing an air gap, such as that shown in the Gerritsen, et al. patent, in place of the UV-curable resin of layer 12 in the Ishii patent, goes against the teaching and rational set forth in the Ishii patent.

The Sakai, et al. patent is merely cited in the Office Action as describing a method of manufacturing optical diffractive gratings having serrated grating portions. Applicant submits that this document fails to remedy the deficiencies discussed above with respect to the Ishii and Gerritsen, et al. patents.

For the reasons set forth above, Applicant submits that the combination of the Ishii, Gerritsen, et al. and Sakai, et al. patents is not appropriate given the disclosure in the Ishii patent. Further, any of those patents taken alone fails to disclose or suggest the features of present invention, in particular, a diffractive grating portion having a pair of diffractive gratings differing in dispersion from each other and confronting each other through a space of a refractive index of 1, wherein a maximum optical path length difference occurring in the diffractive grating portion with respect to each of at least two wavelengths, is m (integer) times a wavelength, and the values of m in the two wavelengths are the same, as generally recited in independent Claims 1, 2, 4, 5, 9, 11, 12, 20 and 22. With respect to independent Claim 21, Applicant also submits that those documents, taken alone or in combination, fail to disclose or suggest at least the features of a diffractive grating portion having a plurality of diffractive grating layers laminated with a space of refractive index of 1, the plurality of diffractive grating layers differing in dispersion from each other, wherein the diffractive grating portion is formed on a light transmitting surface of a lens.

For the foregoing reasons, Applicant requests withdrawal of the rejections under 35 U.S.C. § 103.

The remaining claims in this application are dependent claims which depend from the independent claims discussed above, and are thus patentable over the

documents of record for reasons noted above with respect to those independent claims. In addition, each recites features of the invention still further distinguishing it from the applied patents. Applicant requests favorable and independent consideration thereof.

Also, with respect to dependent Claim 18 (2, 5 and 9), Applicant notes that the Sakai, et al. patent shows a diffraction grating with valley portions having a chamfered shape, wherein the chamfered shape is a curved surface. Applicant submits that that document does not describe valley portions having a chamfered shape which is formed as a flat surface.

This Amendment After Final Rejection is an earnest attempt to advance prosecution and is believed to clearly place this application in condition for allowance. At the very least, the changes presented herein reduce the number of issues on appeal. Applicant requests entry of this Amendment under 37 C.F.R. § 1.116.

Applicant's undersigned attorney may be reached in our Washington, D.C. office by telephone at (202) 530-1010. All correspondence should continue to be directed to our below listed address.

Respectfully submitted,

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JJO/tmm

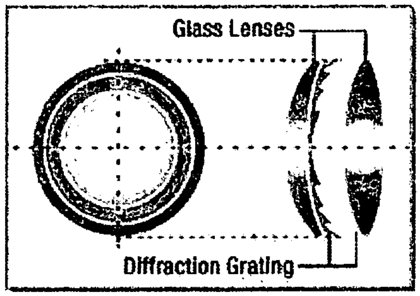
Optical Technology

Multi-Layer Diffractive Optical Element

Excellent picture quality from a new compact optical element

World's First to Be Used in Camera Lenses

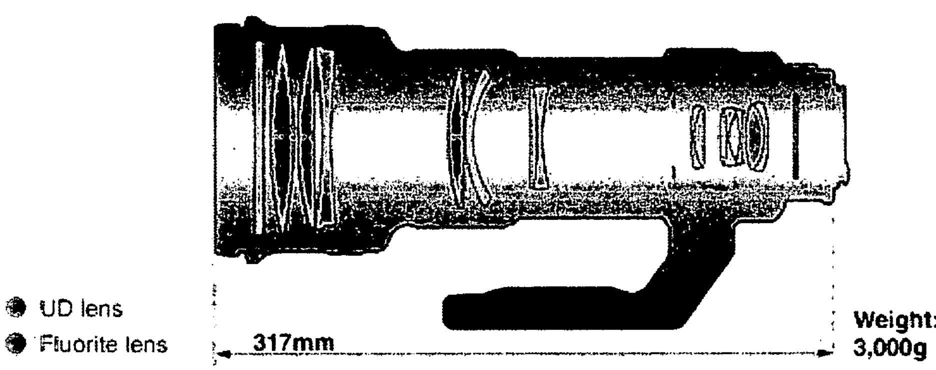
Canon's ongoing quest is to develop cameras that provide startlingly high image quality, yet are extremely light and compact. We have continued to lead the optical technology industry, with major achievements in fluorite, aspherical and free-form surface-prism lenses, opening up new avenues in the process. One successful result of this effort is the world's first Multi-Layer Diffractive Optical Element for camera lenses. This is a revolutionary type of optical element that combines the features of both fluorite and aspherical lenses. Lenses employing this element feature image quality on a par with those of lenses designed solely for conventional refractive optical elements, yet are far lighter and more compact.



Structure of Multi-Layer Diffractive Optical Element (Conceptual Diagram)

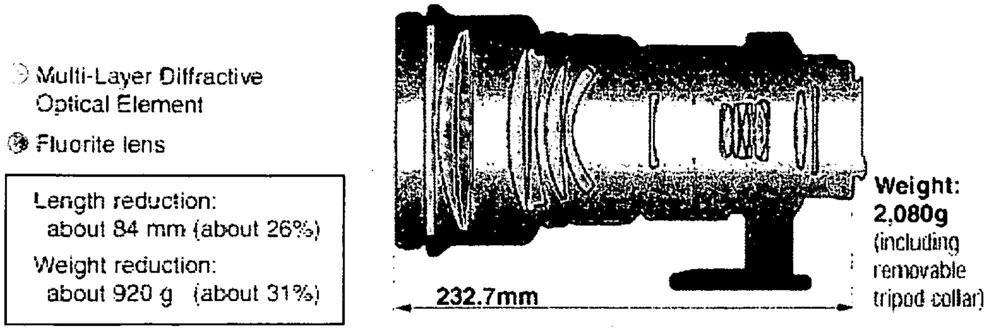
Solving Flares and Other Problems with Micron-Precision Lattice Configuration

Conventional zoom, telephoto and other sophisticated lenses have tended to be large and heavy, since they require combinations of multiple convex and concave lenses to enable their refractive optical elements to correct chromatic aberration (color blur), which lowers picture quality. To address this problem, Canon turned its attention to diffractive optical element lenses, which produce chromatic aberrations that are the exact opposite of those in conventional refractive lenses. By combining it with the refractive lens, Canon developed a lens system with no chromatic aberration.



Lens with a Refractive Optical Element

However, single-layer diffractive optical element lenses tend to have a problem with unnecessary flaring, which makes them unsuitable for camera use. Canon has solved this problem by pioneering a multilayer structure in which two diffractive lattices are placed within a few microns of one another. This has enabled us to make lenses more compact.



Lens System Incorporating a Multi-Layer Diffractive Optical Element

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Using Combinations of Canon Technologies to Produce Ultraprecise Elements

Producing the diffraction lattice of a Multi-Layer Diffractive Optical Element is not an easy task. The precision of lattice height, pitch, alignment and other factors must be refined to submicron levels. Canon introduced proven replica aspherical lens production technologies, including those used in its original 3D ultraprecision processing and EF lenses, as well as highly accurate alignment technologies.

Broad Applications in Imaging Information Devices

In addition to its application to interchangeable lenses in single-lens reflex (SLR) cameras, the Multi-Layer Diffractive Optical Element is expected to find applications in a diversity of imaging information devices, particularly where high image quality, light weight and compactness are required. Examples include glasses-type displays and projection lenses for LCD projectors.

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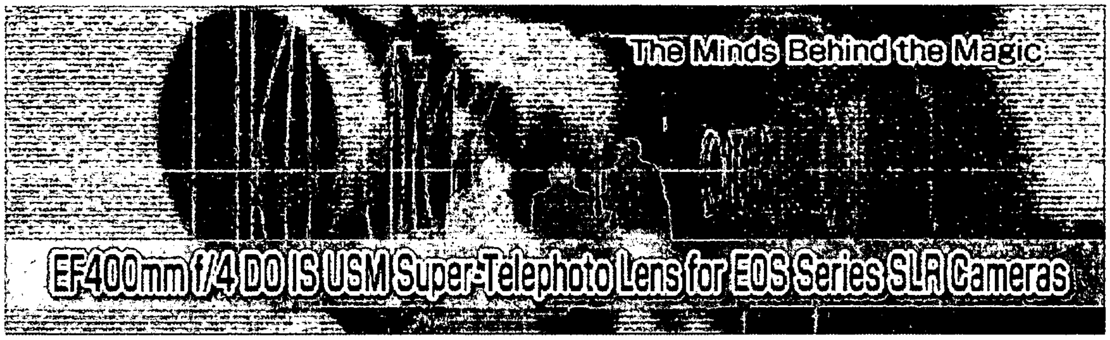

In his General Theory of Relativity, announced in 1916, Albert Einstein postulated that light is bent by gravity. Three years later, on the occasion of a total eclipse of the sun in 1919, a group of British astronomers in Africa proved this hypothesis to be true by measuring the effects on light from stars shining on earth from close to the sun's disc. The discovery, however, led to the anticipation that light from faraway astronomical objects is bent by the gravity of closer, highly dense objects, and is perceived on earth as if through a magnifying camera lens. This phenomenon became known as the Gravitational Lens Effect. Advancements in telescopes and observation instruments, as well as the tireless efforts of astronomers, led to the discovery in 1979 of an object acting as a gravitational lens. The discovery came 100 years after the birth of Einstein.

There exist other phenomena of bending light in addition to gravity, such as reflection, refraction and diffraction. Reflection has been the most widely known light bending method, used in a variety of fields, and refraction also came into wide application in lenses and prisms. On the other hand, the diffractive phenomenon, while vital as a method to determine the crystal structure of substances in scientific fields, has very limited commercial applications, mostly because of the extremely high-level manufacturing technologies required to create diffractive optical elements.

Canon's Multi-Layer Diffractive Optical Element represents a revolutionary "discovery," in that it makes possible the use of the element in camera lenses. This is a story of how gravitic efforts led to the brilliant bending of light, as we meet the engineers involved in this world's first project: the design of the element, development of production techniques, and design of the EF400mm f/4 DO IS USM super-telephoto lens, which maximizes the properties of the diffraction phenomenon.

The Faces Behind the Magic

Takehiko Nakai discovered the principle of the Multi-Layer Diffractive Optical Element and was involved in its design.

Masaaki Nakabayashi was in charge of developing production technologies, particularly press forming and element process methods, for the Multi-Layer Diffractive Optical Elements.

Hideki Ogawa handled the design of the EF400mm f/4 DO IS USM super-telephoto lens, which adopts the Multi-Layer

Diffractive Optical Element, for the EOS series SLR cameras.

Enter the interview page

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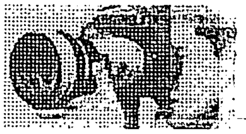


Realizing A "Highly Mobile Super-Telephoto Lens" that Can Be Used Without Tripod

--- The Multi-Layer Diffractive Optical Element is a revolutionary discovery, but I am a little worried that this is going to be a highly technical story. I hope you will start with a simple and easy-to-understand explanation...

"People who really know cameras and lenses are usually surprised at this point..." (Ogawa)

Ogawa: The product itself provides the easiest explanation. As you can see, one of the truly revolutionary features of this lens system is its size. We have achieved a compactness that was impossible with conventional lens design using refractive optical elements.

--- This is it? But it doesn't really seem very small...

Ogawa: Take a look through the camera's viewfinder.

--- .... (Looking through the viewfinder.)

Ogawa: People who really know cameras and lenses are usually surprised at this point...

--- Wow! I'm trying to keep my eyes from popping out of my head! And it seems so light for a super-telephoto lens. (Smiles wryly)

Ogawa: It hasn't been on the market for very long, but we have already received some user response that its low weight is especially evident when carrying the camera for a long period of time, or moving it around during heavy use. We have also heard from users who say they are getting more shooting opportunities with the new lens.

Nakai: One photographer of wild birds exclaimed that he could even run with the camera on mountain trails!

--- I see. So it lets photographers get the shots they would have missed before. That's a feature that is certainly easier to understand than image quality and the optical elements.

Ogawa: Other features, such as the image stabilizer, which compensates for camera shake, gives the advantage of two or three shutter speed settings, and the ultrasonic motor realizes fast focusing. All this, and it's lighter, and shorter than comparable lenses.

--- The shorter length brings the center of gravity closer to the camera body itself, which makes it easier to balance?

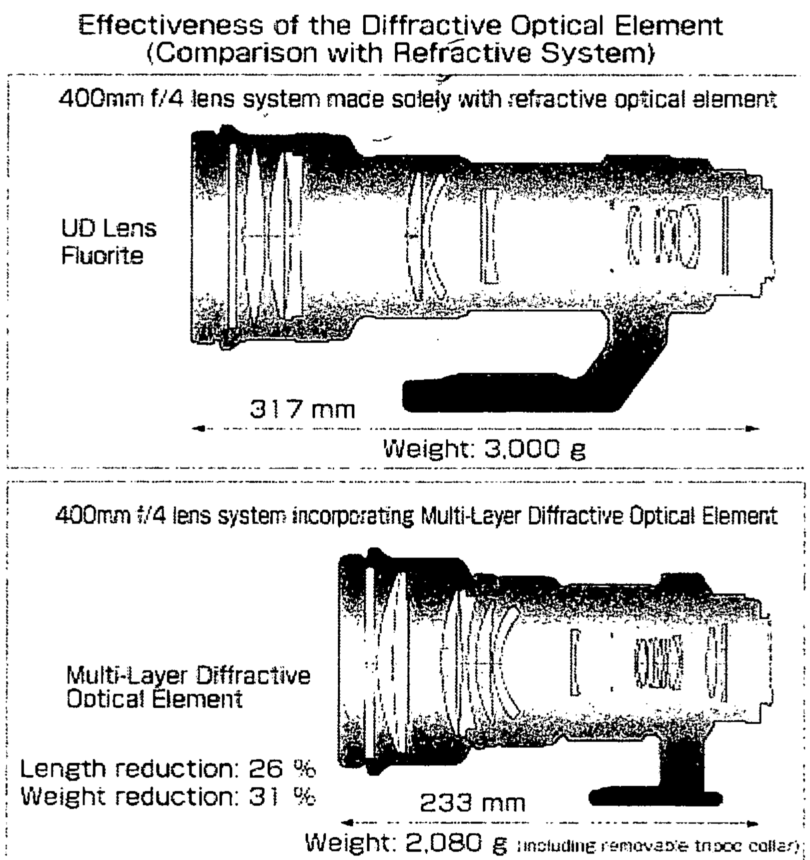
Ogawa: That's it exactly! You know your stuff about lenses. (Laughs) In other words, this is a highly mobile super-telephoto lens.

--- It's wonderful. What about the price?

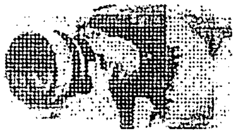
Ogawa: It's wonderfully priced, though at the high end of the market.

--- Breathtaking! (Laughs) I guess that the target user would be a professional photographer?

Ogawa: We especially have sports photographers in mind. With this lens, they can hold the camera in their hands while tracking continuous shots of fast scenes, which used to require a tripod or monopod. We barely made it in time for the Winter Olympics in Salt Lake City, but the release was well in advance of FIFA World Cup 2002. It's my personal opinion that we've added one more element of fun ourselves to the soccer action. (Laughs)



▲Canon's newly developed Multi-Layer Diffractive Optical Element made possible reductions in lens system weight of 30 percent or 0.9 kg, from systems using only fluorite lens elements. This compactness allows photographers to fit the lens together with the camera into a regular camera bag.



Dual-Layer Diffractive Lens—The Issue Was Whether It Could Be Made

--- But what exactly is the Multi-Layer Diffractive Optical Element? Does it mean an optical element with several diffractive layers?

Nakai: By multi, we mean two layers attached together, rather than a single layer. An optical element refers to an individual lens. In other, friendlier words, the Multi-Layer Diffractive Optical Element can be called the Dual-Layer Diffractive Lens.

--- That clears things up a little bit.

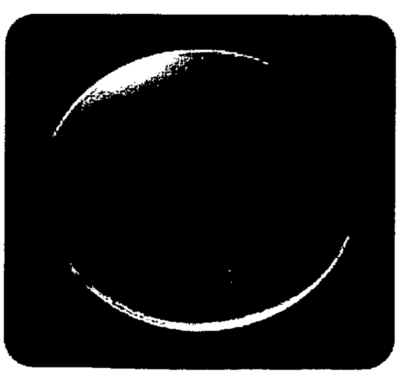
Nakai: As you know, light is a phenomenon of wave motion. Diffraction can be used to superimpose or eliminate waves, precisely controlling the direction in which light travels.

--- Yes, I think I understand.

Nakai: Optical elements making use of this principle have been adopted in measuring instruments and the lens of optical disc pickup systems. But this is the world's first example of such optical elements being used in a camera lens.

--- In my research for this interview, I noticed on the Web that you had received a major Japanese academic award for this lens, and that you were invited to present your achievement. I didn't understand a thing after reading the brief for your presentation, but I got the idea that this was a revolutionary discovery. You were also listed as *Professor* Nakai and from this point, is that how I should address you? (Laughs)

Nakai: It was very embarrassing. (Laughs) My face turned purple under the spotlights, but most of the response was praise for the manufacturing. (Laughs) After all, this optical element was truly difficult to produce.



▲The diffractive lens has a wide diameter of 10 cm. In

--- This is the element itself?

Nakai: Yes. At first glance, it looks like your average concave lens, but if you look closely, you should see a concentric pattern of stripes.

--- I see it. Yes, I see it. They are engraved at rough intervals at the center, but the striped pattern becomes finer and almost nonexistent as you reach the outside perimeter...

Nakai: There are about 150 stripes in all. Adjusting the width of the gratings converges

development, close attention was paid to visual appeal, such as the attractiveness of the striped pattern, in addition to optical performance.

light in the same way as lenses. The finer the width, the greater the level of light bending.

--- You mentioned two layers attached together, so what I am seeing here is two layers times 150 stripes?

Nakai: No. The stripes of the two layers match perfectly.

--- A perfect match? But the two lenses are produced separately, and then attached, right? How perfect can the match be?

Nakai: To the micron level. The difference can't be detected by the naked eye.

--- Making two individual lenses with such a perfect fit is difficult enough in itself, but I imagine exactly matching them must be a superhuman effort.

Nakai: The hard parts were figuring out which striped pattern would best produce the desired lens performance, and then actually producing the lenses in line with the design.

--- I have to admit that this is quite an achievement. What was your objective at the design stage?

Nakai: Objective? First I had to confirm whether the lenses could be produced at all.

--- That would be the basic problem. (Laughs)

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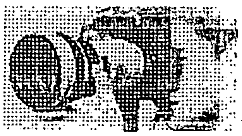


Shopping at Chemicals Companies for the "Ideal Resin"

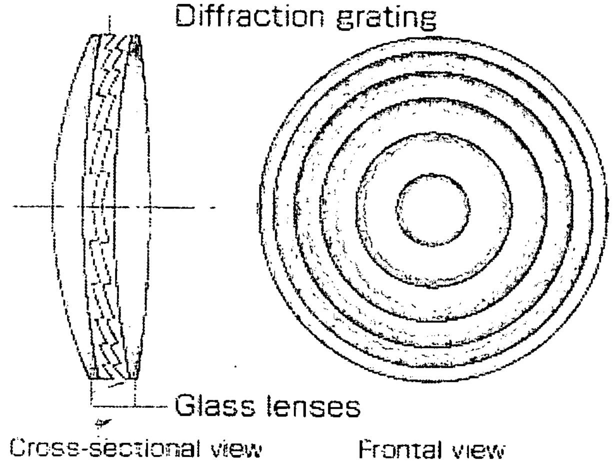
--- So what exactly is this striped pattern made of?

Nakai: It was formed using a mold with a special resin. A magnified cutaway view shows ridges like the teeth of a saw. These ridges appear to be stripes when viewed from the front with the naked eye.

--- These are ridges in the cross-section of the lens?

Nakai: Yes. We had a trying time getting those ridges just right, but before that was the equally difficult task of finding the right ingredients. That part was left up to someone else, though.

Multi-Layer Diffractive Optical Element



▲The configuration formed by the resin becomes a diffraction grating that bends light. The optical performance of the lens is greatly influenced by the grating height, width and shape of the gratings, and by the material characteristics of the resin through which the light passes.

--- Nakabayashi-san's job?

Nakabayashi: Yes, I was in charge of shopping for and shaping the right ingredients.

--- Nakai-san said a special resin was needed for the ridged area. Just how special?

Nakabayashi: Nakai-san told me what kind of characteristics he needed, and asked me to find the material that met those conditions. The first thing I did was to approach chemicals companies, but their first response was, "You won't find anything like this anywhere on the planet" or "It may be available only in liquid form."

--- Oh no!

Nakabayashi: The request was for a moldable material that could provide the desired optical performance. But such a material really didn't exist.

--- But here is the lens right in front of me, so the material had to exist somewhere on the planet...

Nakabayashi: I looked and looked. One of the conditions was that the material had to have a large dispersion...

--- Which means?

Nakai: The desired material would produce large variations in the angle of light curvature at different wavelengths of light.

--- Is this related to color blur or something?

Nakai: None other. We needed a material that would provide a large color blur, or chromatic aberration.

--- But in a normal lens, wouldn't that kind of material be useless?

Nakabayashi: That's why it was so difficult to find! Chemicals companies usually spend their time trying to develop materials that minimize chromatic aberration. What we wanted was exactly the opposite.

--- In other words, you had to go on a quest for the right material?

Nakabayashi: I searched through all the available literature. Once, when I finally got a lead and contacted the company involved, I was told that the relevant research had been halted. There were researchers who worked very hard to develop such a material a decade or two ago, but this is a very complex field, and issues existed as to whether such materials would generate a return on the development investment. Most such projects were shut down. I asked some companies if they would make the attempt for us, but most of the answers I got were, "Is Canon going to pay for the research?" or "Maybe next time."

--- None of the answers were the right color, then.

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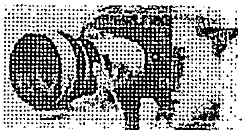

Bargaining on the Edge with Chemical Engineers

Nakai: But this was an optical characteristic we really needed. The design would fall apart without it...

Nakabayashi: I couldn't find the right material in any catalog or specifications list. There were back and forth exchanges every time I told chemicals companies what Nakai-san wanted, I had to go back to Nakai-san with negative responses such as "Preposterous" or "Impossible" or "Unfeasible."

--- I might have given up then. How many companies did you approach?

Nakabayashi: If you include the ones that didn't even stop to listen, every leading and mid-level company in the industry. I went to quite a few small companies, as well. Finally, I got to one of the top manufacturers. Of course, they didn't have anything like this available, but they did have a material in the research phase that would meet Nakai-san's design specifications.

--- But don't the big chemicals companies work only in quite large volumes of materials?

Nakabayashi: You got it. I was asked how many tons of the material per month Canon would purchase. What could I say?

Nakai: The most I needed for a single element was 0.6 grams. Even at 1 gram, that would only be 100 grams per 100 lenses, or one kilogram per 1,000 lenses. If we were talking in tons... (Laughs)

Nakabayashi: I think the company finally saw the potential of what we were trying to achieve. Quite a few chemicals companies have stick to their guns and want to create the world's best materials. The engineer I spoke with said, "I really want to try to make this material, so please make your request (to management) as strong as possible."

--- You were made a partner in crime, as it were. (Laughs)

Nakabayashi: When you're in contact with another engineer, they're usually interested in what you are trying to produce, and that makes for lively discussion. Of course, I couldn't reveal the entire project, so we ended up sounding one another out. But the inevitable end of this process was volume. I kept hoping that I could ask for a ton or two, even more. (Laughs)

--- Absurd! (Laughs)

Nakabayashi: In the beginning, we didn't even know ourselves how far this project could go. (Laughs)

"The material itself was produced through a "bargaining" of various characteristics to bring out the desired special optical performance." (Nakabayashi)

--- In the end, though, your bargaining resulted in the birth of a new material.

Nakabayashi: Yes. The feeling that we must succeed at all costs only grew after we received our first samples from the chemicals company. The material itself was produced through a "bargaining" of various characteristics to bring out the desired special optical performance. The company created an uncountable number of samples of finely blended materials as we narrowed down the possibilities.

--- And is this lens the only product using this special material?

Nakai: The only product in the world right now. The competitors might have also developed such a lens if the right material were easy to find. I was really impressed with Nakabayashi-san's work.

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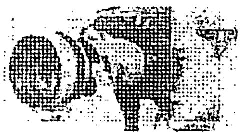
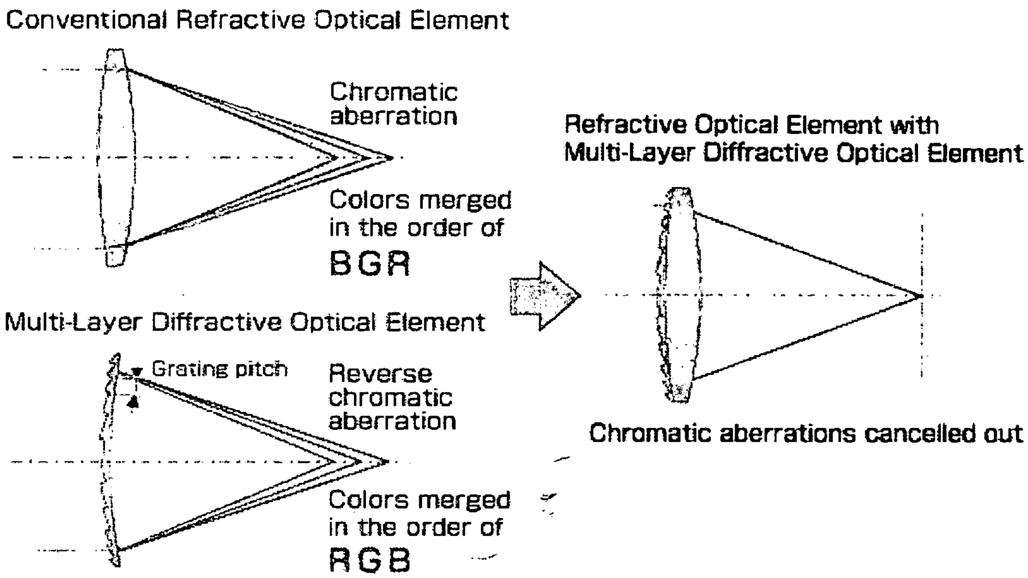


A Lens that Removes Chromatic Aberration in Exactly the Opposite Way that Refractive Lenses Do



▲With the refractive lens, light in the red band (long wavelength) focuses at a far position, while with the diffractive lens this light focuses at a close position. In refractive lens systems, chromatic aberration is eliminated by using both convex and concave lenses. With an optical element offering the characteristics of both a diffractive and a refractive lens, the job is completed with a single element.

--- I haven't yet asked you an important question. Why does the diffractive optical element lens work with two layers, but not with one?

Nakai: Before we go there, let me explain a little about diffraction itself. Conventional lenses use refraction to bend light (RGB), but refraction makes it difficult to bend light in the red band. You can see what I mean if you hold a prism under sunlight. Light in the red band has a longer wavelength, and is therefore more difficult to bend than blue- and green-band light.

--- What happens with a diffractive optical element lens?

Nakai: Red-band light bends much more than the other two light bands. The extent of bending depends on the wavelength, but because of the longer wavelength of light in the red band, the angle of diffracted light is larger.

--- What you're saying is that the action of bending light using diffraction is the opposite of that with refraction? I think I'm beginning to understand.

Nakai: To eliminate chromatic aberration, conventional lenses using refraction have to take light that is sharply bent through a convex lens and return it through a concave lens. The color-elimination effectiveness is larger with diffraction, so there is no need for a concave lens, and the light doesn't have to

be bent to such a great extent.

Ogawa: Which makes designing the lens system easier. And with the diffractive optical element lens, we could autonomously adjust for chromatic aberration without affecting aberrations such as that of the spherical surface.

--- The lens is that good. But why isn't one layer enough?

Nakai: The answer would be, "Because the diffraction efficiency would be unfavorable with one layer." When we tried to bend light with a single layer, light would be bent not only in the desired direction, but in other directions, as well. In camera lenses, the result would be photos with double images.

--- That would not be a good thing.

Nakai: The diffractive optical element lenses used in optical pickup systems and measuring instruments handle only lasers, which have a single light wavelength. Thus, lenses can be designed specifically for the desired light wavelength. However, this is not the case with camera lenses, which handle natural light comprising a variety of light wavelengths. By placing another layer right next to the first, we are able to make the chromatic adjustment before unwanted flares are generated. This is why we needed a material with high dispersion. This is the basic idea behind the project.

--- But, according to the theory of diffraction, isn't bringing the layers close together all about the order of the light wavelengths?

Nakai: Yes. At the closest point between the layers, the interval between gratings is several microns, the distance of two or three wavelengths. The grating pitches, grating heights and width of the space between the gratings had to exactly maintain the shape and width values specified in the design.

--- What a level of precision!

Nakai: That's where the problem of whether or not it could be made came up. We found the right material, so the next hurdle was the mold to actually produce lens.

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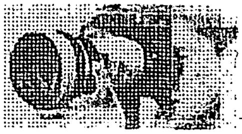


Straining to the Limit to Form Micron-Level Gratings

--- The production of ultraprecise molds lies at the core of the competitiveness of industry in Japan. It's a vital area.

Nakai: And molds for lenses must be more precise than any other. Normally, the required precision is achieved by polishing the mold after carving using cutting tools. But with the mold for a diffractive optical element lens, polishing would remove the peaks of the gratings, which means we had to achieve the required precision through the cutting process alone. It took us six months of repeatedly cutting mold itself, press forming and measuring lens before we got the precision we wanted.

--- Does the mold processing require quite a bit of time?

Nakai: The processing time itself is short. But the preparations take time, from adjusting and warming up the equipment, to the idling time after everyone leaves the processing room. We had to eliminate every factor that might affect the precision of the mold, such as temperature variations and other adverse effects of body temperature that might result from having a person in the processing room.

--- And you had to remove all external vibrations?

Nakai: Of course. At one point, road construction work was going on outside the building, forcing us to come in on weekends, when the construction wasn't taking place.

--- Were the teeth of the cutting tool for the mold also ultraprecise?

Nakai: We used diamond cutters. To achieve the precision we needed, we used only the highest quality diamonds available, and we even went so far as to consider the direction that each diamond crystal faced. The mold processing took place in a different location from the lens design work, so I had to make many trips...

--- Designers don't usually have to visit the mold processing facility.

Nakai: You're right. Actually, I visited a Kannon Buddhist Temple near the processing facility to pray (that the molding process would be a success) every time I went there... And later I would have a mold in my hands, and let Nakabayashi-san know the results.

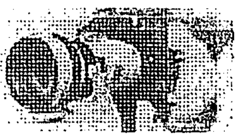
Nakabayashi: The lens press forming team would

then use this mold to create a diffractive optical element lens with gratings aligned in a concentric circle. The resin is poured into the mold and rapidly made uniform while being carefully stretched so as to not leave any air bubbles. This is the work of an expert. When the resin is stretched, it is very delicately affixed to the glass, and then solidified by applying light.

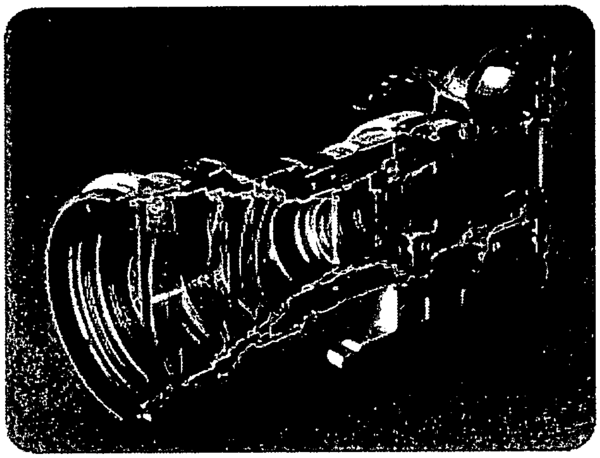
--- You used a resin that solidifies under ultraviolet light?

Nakabayashi: Yes. When it is solidified, it is removed from the mold with extreme caution to avoid breaking any of the gratings. The slightest carelessness would mow down the ridges of the micron-level grating, and even a tiny scratch could make the entire mold useless. Every moment was extremely tense.

"Actually, I visited a Kannon Buddhist Temple near the processing facility to pray (that the molding process would be a success) every time I went there..." (Nakai)



The "Experts" Who Make Possible Submicron Precision



▲Cutaway model of the EF400mm f/4 DO IS USM lens mounted on the EOS SLR camera. The large-diameter diffractive optical element lens placed at the forefront of the lens system realizes a compact super-telephoto lens.

Nakai: In the beginning, it would have been enough to say, "We're almost there! That's the performance we need!" But as the process was repeated again and again, everyone became more nervous. We might have success trying one method, but not achieve the same performance a second time using that same method.

Nakabayashi: Sometimes what the eye perceives is slightly different from what is expected, even if all the measurements meet the proper values. We've experienced the fact that the perceptions of an expert surpass the precision of measuring instruments.

Nakai: We thought about using an electron or atomic force microscope, but the diameter of this diffractive optical element lens is 100 mm. No microscope with that scale of precision is big enough to handle this size. What's more, the purpose of such ultraprecise microscopes is to examine flat surfaces. The lens has a grating surface and is also curved. Besides, if we accidentally bumped the lens while examining it, we would be in real trouble.

Ogawa: If you think of this lens as a town with a diameter of 10 km, the permissible surface roughness would be about the thickness of a piece of paper. That's how smooth the surface has to be.

Nakabayashi: The heights of the diffraction grating, or the walls of the grating, are 7.9 and 10.7 microns. Measured at the 10 km range of a town, this becomes 79 and 107 cm. None of these walls can be 78 or 108 cm. Not a single rock could be allowed to fall into any of the town's sewers, and not a single line of graffiti could be allowed on the walls.

Ogawa: The slightest fault would instantly cause flares.

--- I am speechless.

Nakai: In terms of skills, the best of the best are required for both the mold processing and the resin press forming, the kind of specialist who can center

the cutting machine with less than a micron of precision on the first try.

--- That's a pretty special person for a pretty special mold. You might even get performance beyond what the design calls or? (Laughs)

Nakai: Certainly the kind of person who you think just might give you that kind of result. (Laughs)

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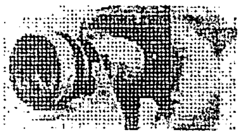
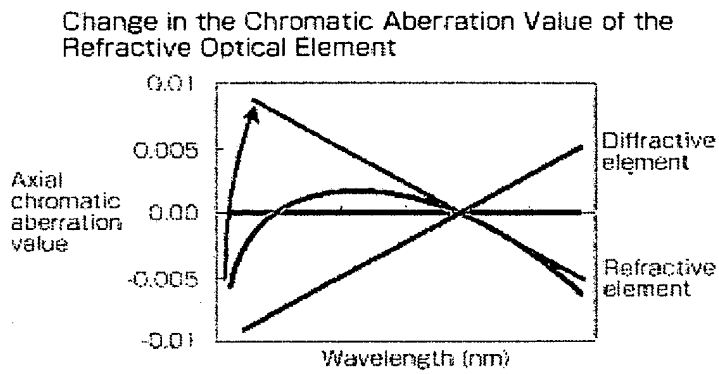


The Unexplored Wide and Astonishing Zoom —— Canon's Diffractive Optical Element Lens Expands Possibilities

--- Ogawa-san, you said that the diffractive optical element lens makes designing lens systems easy. What is the main difference from conventional lenses to date?



▲The color (wavelength) of light coming into the lens determines the level of color blur (axial chromatic aberration value). The curving red line in the graph shows the color blur of a conventional refractive lens, while the straight blue line shows the color blur of the diffractive optical element lens. Designing a lens system in which the characteristics of the two lenses cancel one another out (straight purple line) provides optimal color aberration cancellation (horizontal black line).
(The reciprocal number of the slope of the graph is the Abbe's Number.)

Ogawa: I could say the Abbe's Number, a measure related to chromatic aberration. Lens designers are always in search of materials with low Abbe's Numbers. With materials that have a large Abbe's Number, such as fluorite, the chromatic aberration generated tends to get smaller, but when you try to make the lens system more compact, it becomes difficult to achieve the right balance with other aberrations.

--- Fluorite is an excellent lens material. Do you mean that a special kind of difficulty arises when you try to make the whole lens unit smaller?

Ogawa: Yes. On the other hand, materials with smaller Abbe's Numbers generate larger chromatic aberrations, but the effect on other aberrations is minimal when reducing the lens unit size, and chromatic aberration can be controlled to a greater extent.

--- And the diffractive optical element lens has an Abbe's Number close to zero?

Ogawa: Very close. In fact, the number is negative.

--- Boy, a lens from wonderland.

Ogawa: A material with a negative Abbe's Number allows us to simultaneously adjust chromatic aberration at the center of the surface (axial chromatic aberration) and the perimeter (lateral chromatic aberration).

--- And no other lens like it has existed before?

Ogawa: None at all. Of course, a certain degree of related design theory is needed, but the diffractive optical element lens does a superb job of resolving one of the most difficult hurdles facing lens designers. As a result, lightweight and low-cost glass, which could not be used previously, become viable in other parts of the lens system. For our first attempt, we maximized the lens' capabilities to produce compact and lightweight super-telephoto lens.

--- The lens that lens designers have been waiting for.

Ogawa: My first thought was that we had achieved the ideal in optical elements. The concept of using a diffractive optical element lens to remove color aberrations has been around for decades. They would have been considered good stock if those odd flares didn't occur, but such was not the case. One remarkable factor in this project is the elimination of flares through the use of dual layers.

--- Then this really is a huge discovery. When did you come up with the idea, Professor Nakai?

Nakai: Please, leave off the "Professor." (Laughs) If memory serves, I used to walk around wondering, "What is diffraction?" and "Why does light bend?" I would stop whenever I saw a light flash. I think I was scaring the people around me for a time. (Laughs)

--- And then it hit you, like the apple falling on Newton or a light bulb switching on in your head?

Nakai: Hmm. That was at about the time I got married, so it wasn't quite that dramatic.

--- Come on, you know the old saying that people do well in pairs, just like layers. (Laughs) Ogawa-san, you mentioned that your aim was to create a compact, lightweight super-telephoto lens. What comes next?

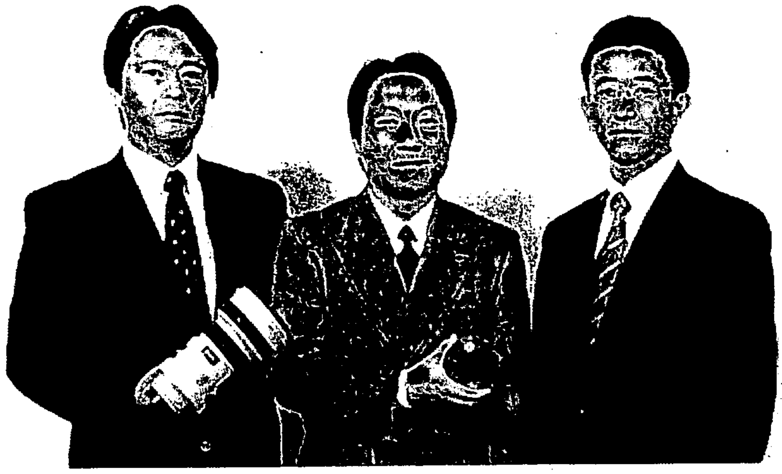
Ogawa: A wide-angle lens. The diffractive optical element lens is a godsend, completely removing color aberrations that even fluorite cannot deal with. I think that, right now, it is the only optical element that can handle chromatic aberration adjustment in a wide-angle lens.

--- So it won't be long before we see wide-angle diffractive optical element lenses, lenses for digital cameras, and zoom lenses...

Ogawa: It is a lens with a great many possibilities.

Nakabayashi: Right now, the diffractive optical element lens is like a handmade product. We have to make progress in the manufacturing techniques, as well.

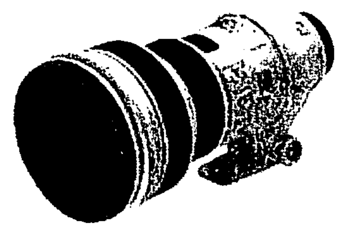
--- I hope you can get those material orders to the ton level soon! (Laughs)



This article is based on an interview conducted and information available in the spring of 2002.

Canon

Diffractive Optics



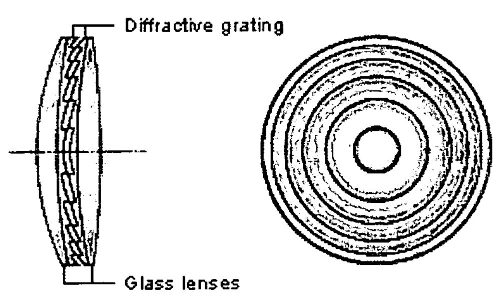
EF 400mm f/4 DO IS USM

A quick definition will help you understand this exciting new Canon lens technology. Glass lens elements refract, or bend lightwaves as they pass through it to form an image. We use multiple elements and special glass to keep the lightwaves like a pinpoint instead of spreading them into the rainbow of color you see when light passes through a prism. To diffract lightwaves means that the ray goes through a change in direction before passing through the lens. The change in direction is caused by a diffraction grating — very fine parallel groves or slits on the surface. Canon uses two single-layer diffractive optical elements whose diffraction gratings are bonded together face-to-face. The diffraction that occurs with Multi-Layer Diffractive optical elements actually corrects the optical system's chromatic aberrations and improve the image formation performance.

Why is Canon changing the tried and true physics of lens design? In terms of design and manufacture, it allows us to create lenses that are shorter and lighter than comparable refractive optical systems. The 400mm f/4 DO IS USM lens is approximately 27-percent shorter and 36-percent lighter in weight than a conventional 400mm f/4 telephoto lens would be. Image quality of Canon's DO lenses are comparable to our L-Series, offering photographers very high performance.

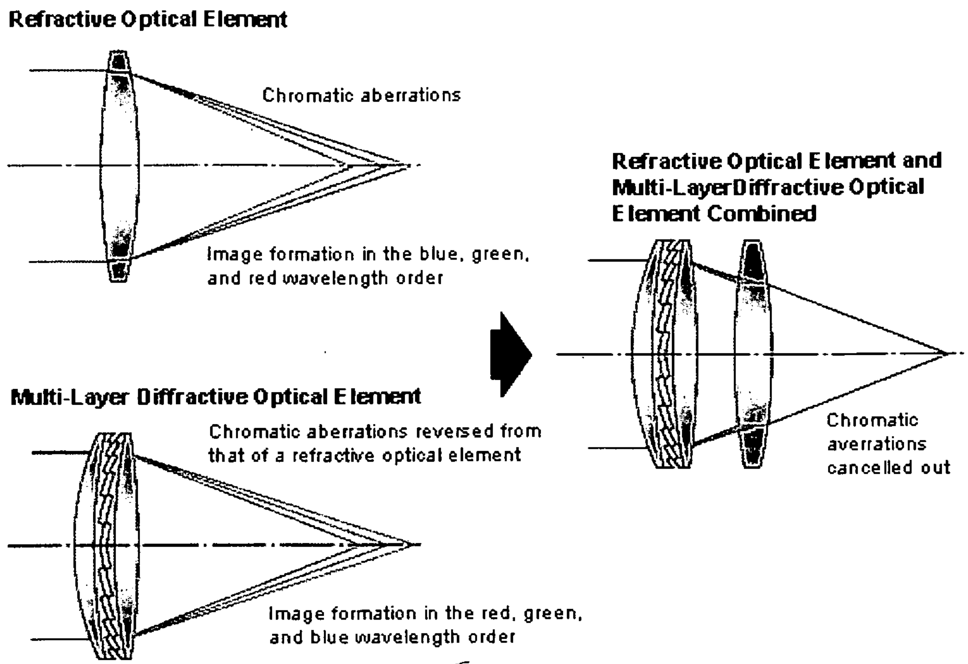
Note: If a very bright spotlight like a mercury lamp is photographed with a DO lens, a ring of light may occasionally appear around the light source, due to the imaging characteristics of the multi-layer diffractive optical element.

■ Multi-Layer Diffractive Optical Element Construction



Cross section **Front view**

■ Correction of Chromatic Aberrations by the Multi-Layer Diffractive Optical Element


Refractive Optical Element
Chromatic aberrations
Image formation in the blue, green, and red wavelength order
Multi-Layer Diffractive Optical Element
Chromatic aberrations reversed from that of a refractive optical element
Image formation in the red, green, and blue wavelength order
Refractive Optical Element and Multi-LayerDiffractive Optical Element Combined
Chromatic averrations cancelled out